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NAVAL AIR WARFARE CENTER AIRCRAFT DIVISION
PATUXENT RIVER, MARYLAND

TECHNICAL REPORT

REPORT NO: NAWCADPAX/TR-2012/194

POPULATION DENSITY MODELING TOOL

by

Davy Andrew
Michael Knott
David Burke

26 June 2012

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DEPARTMENT OF THE NAVY
NAVAL AIR WARFARE CENTER AIRCRAFT DIVISION
PATUXENT RIVER, MARYLAND

NAWCADPAX/TR-2012/194
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SUMMARY

The purpose of this report is to develop a method to calculate the population density within the flight path and potential crash area of an unmanned aircraft. A method based on U.S. census data for the continental U.S. is described along with calculation methods and analysis of results.

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INTRODUCTION

Expanding the permitted airspace permissions for Unmanned Air Systems (UAS) is a common desire among multiple military and civilian government organizations. Military groups desire to expand the UAS airspace to improve reserve and operational logistics, training exercises, and testing purposes. Civilian agencies, such as police forces, border patrol, and news agencies, would use unmanned air vehicles to conduct aerial surveillance and other missions strongly suited to the UAS. Current air space restrictions limit flight to either restricted airspace, or areas with sparse populations. While lifting these restrictions would have a positive impact on operational envelope and flexibility, due diligence must be used to ensure the public is not subjected to unreasonable hazards.

One of the critical requirements for expanding the operational area of UAS is to understand the risk to uninvolved third parties on the ground posed by the crash of a UAS. In order to address this issue, Office of Secretary of Defense, Strategic and Tactical Systems – Unmanned Warfare Office, has sponsored the Target Level of Safety (TLS) to Third Parties program. The objective of this program is to define a consistent calculation method to determine the relationship between UAS reliability, potential to cause damage, and where it flies. NAVAIR (AIR-4.3.1) has lead the effort to develop this methodology. The TLS Program includes 5 modules; Casualty Expectation, Probability of Loss of Aircraft, Potential Crash Location, Lethal Crash Area, and Population Density.

The basis for the TLS Methodology is a risk assessment tool called the 3rd Party Risk Analysis Tool (3PRAT). By using the 3PRAT, a Level of Safety (LoS) can be quantified for any aviation asset flying over the National Airspace. The end goal of the analysis done with the 3PRAT is to quantify the risk of air operation for third parties on the ground. 3rd party individuals consist of those who are not on aircraft and those who do not work on or around aircraft. This encompasses the vast majority of the U.S. population for any given point in time. The LoS generated from the 3PRAT will be evaluated to determine what the risk of air operations is. For more information regarding the 3PRAT, please refer to *Third Party Risk Assessment Tool (3PRAT)* (Knott, 2012).

The equation used to calculate LoS is listed as equation 1.

$$LoS = PLOA * POCA \tag{1}$$

where:

LoS = Level of Safety (fatalities per 100,000 flight-hours)
PLOA = Probability of Loss of Aircraft (loss per 100,000 flight-hours)
POCA = Probability of Casualty(fatalities per loss)

This report focuses on the Probability of Casualty (POCA) aspect of the above LoS equation. POCA is simply the expected casualties given that an aircraft impacts the ground. POCA is defined by equation 2 and has the units of fatalities per loss.

$$POCA = LCA * Population\ Density \tag{2}$$

where:
POCA = Probability of Casualty (fatalities per loss)
LCA = Lethal Crash Area of Aircraft (square miles)
Population Density = The average population density within the Potential Crash Area (PCA) (people per square miles)

The LCA component in equation 2 has been previously calculated in the 3PRAT. The methodology used to determine the LCA is outlined in the report: Crash Lethality Model (Ball, 2012), reference 1. Given the LCA of the aircraft, the next step is to determine the population density of the Potential Crash Area (PCA). This is accomplished in two different steps. First the PCA of the aircraft must be determined. The methodology used to determine the PCA is outlined in the report: Potential *Crash Location Model* (Bradley, 2011), reference 2. Once the PCA is determined, the average population density bounded within the PCA must be calculated. That is the purpose of this paper and is the basis for the following discussion.

POPULATION DENSITY

As previously stated, in order to determine the probability of casualties for a specific aircraft crash, the population density must be determined for the given PCA. The population density for any given area is just a function of the localized population divided by the area in question. This can be shown in equation 3.

$$PopDen = Pop/Area \tag{3}$$

where:
PopDen = Population Density (people per square mile)
Pop = Population (people)
Area = Area (square miles)

To determine the population for the PCA, data collected from the U.S. Census Bureau was used. The population of the U.S. is analyzed by the Census Bureau every 10 years when the U.S. Census is conducted. The census data will be the foundation of the data used for the methods outlined in this report. Due to the fact that the TLS tool is primarily concerned with the risk to 3rd parties on the ground within the national airspace, the Continental United States will be the land mass analyzed for the tool. Alaska, Hawaii, or any territories of the U.S. will not be analyzed for the purposes of this tool. However, if the need arises for these landmasses to be analyzed, they can easily be added to the tool.

CENSUS DATA

In 2010, the U.S. Census Bureau conducted the 2010 census. The data are available on the Census Bureau’s website (Census Bureau, 2012), reference 3, in the form of shapefiles. A

shapefile is a popular geospatial vector data format used by many geographic information system software packages. These shapefiles were available from the Census Bureau in many different resolutions to include: census blocks, census tracts, congressional voting districts, school districts, counties, county subdivisions, etc. The resolution structure used by Census Bureau can be seen in Figure 1.

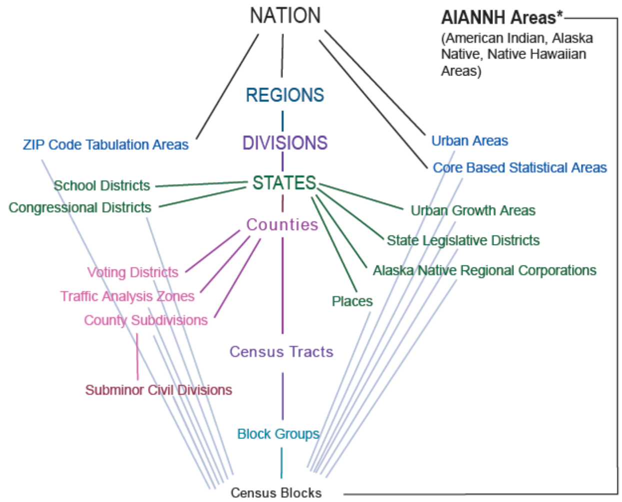

Figure 1: Standard Hierarchy of Census Geographic Entities

CENSUS BLOCKS

As it can be seen in Figure 1, the highest resolution offered by the Census Bureau is census blocks. The census blocks are not uniform in geometry or size. The census block can vary in size from sections of city blocks to square miles of farm land. Each block also varies in geometry with there being millions of different polygons used to depict census blocks across the country. This created some challenges when trying to evaluate the data.

Another issue that arose when evaluating the data was that the census blocks resolution exceeded the computational capability of the computers used for this analysis. As an example, the state of California contains over 710,000 census blocks. Within each census block, there are 11 channels of data that include: longitude (x), latitude (y), population, state identifier, etc. For the state of California alone, there were over 7,810,000 data points that the programs used to cache, plot, and store. This proved to expend the virtual memory of the computers being used. For smaller states, the virtual memory of the computer was not exceeded; however, due to the amount of data, computations and plotting could take in excess of an hour. As a result, the census blocks were found to be unusable. It was determined that in the case of a majority of the U.S, census tracts; two resolution steps up from census blocks, would be an adequate resolution for use in our analysis for most cases. However, it was found that in some cases, census tracts would not be an adequate resolution.

In a couple large western states with low population, census tracts were found to be an inadequate resolution. The state of Wyoming for example only has 133 census tracts. The average area of a census tract had an area of 735 square miles. This proved to be too low of a resolution for the purpose of this analysis. As a result, for states with inadequate census tract resolutions, census block groups were used. By using census block groups, the resolution for the state of Wyoming was increased from 133 to 411. The specifics on census tracts and census blocks will be discussed further in the next section.

CENSUS TRACTS AND CENSUS BLOCK GROUPS

Census tracts and census block groups much like census blocks vary in size and geometry. As a comparison between census blocks and census tracts, Figure 2 shows an example of Rhode Island with the census blocks and census tracts displayed.

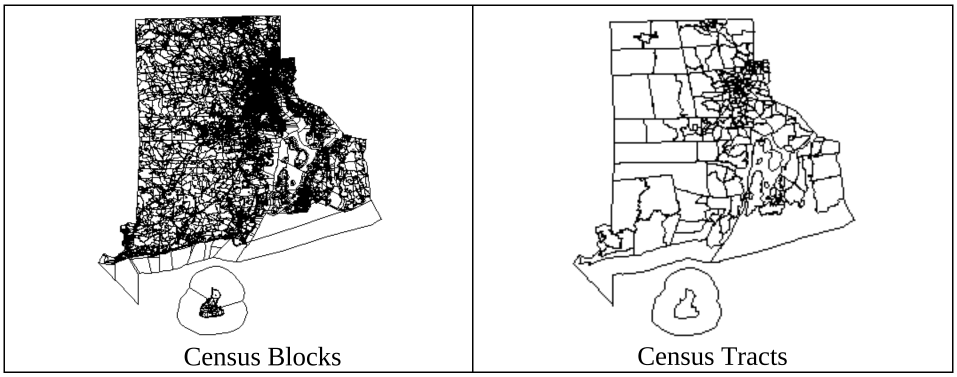

Figure 2: Rhode Island Drawn with Census Blocks and Census Tracts

As it can be seen in Figure 2, as the population of an area increases so does the resolution of the census tracts. In urban areas, the resolution of census tracts increases while it decreases in more rural areas. Using California as an example, there are just over 8,000 census tracts in the state as compared to the 710,000 census blocks. By switching from census blocks to census tracts, the amount of data used was reduced by two orders of magnitude. For most states, census tracts were an adequate resolution for analysis. As previously stated however, when analyzing some western states, census tracts proved to be inadequate. To determine which resolution would be used for each state, the land mass was compared to the number of tracts. If a state had an average census tract area of more than 250 square miles, the resolution was increased to census block groups.

The average block area of less than 250 square miles showed to give enough resolution due to the fact that as the population of an area increases, so does the resolution of the blocks used to depict the census block groups. The very large blocks tend to be located in unpopulated areas where the size of the block did not have a statistical impact on the calculation of the population density.

When switching from census blocks to a lower resolution, it had to be determined if the decrease in resolution provided enough data to accurately complete the analysis. To do this, the PCA of varying aircraft was evaluated and plotted against the state of Virginia's census tracts. Considering one scenario, the RQ-2B Pioneer UAS was evaluated at an operating altitude of 10,000 ft and airspeed of 100 kt. The resulting PCA can be seen in Figure 3 outlined in red. In this case, the resolution used for the state of Virginia is census tracts.

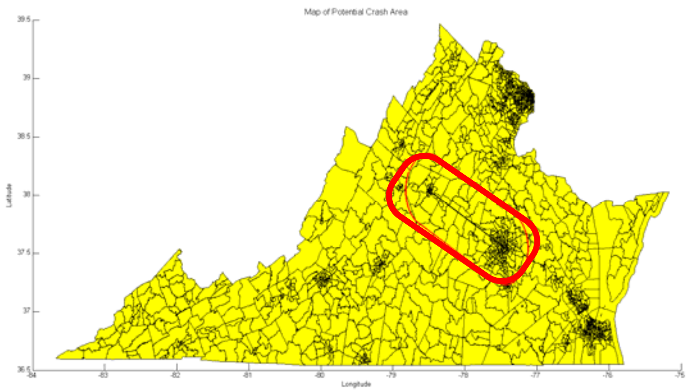

Figure 3: RQ-2B Pioneer PCA over Virginia

When using census blocks the calculated population density within the PCA was 317.74 people per square mile. Using census tracts, the calculated population density within the PCA was 336.28 people per square mile. This produced only a 5.83% variance in the population density data. Based on this relatively small error and drastically reduced computational time required, it was determined that census tracts did not have a significant impact on calculating the population density and, as a result, they will be used for this tool.

POPULATION DATA

After downloading the census tract data from the Census Bureau, it was discovered that they did not include population data with any resolution other than census blocks. This created a problem when trying to use census tracts and census block groups to determine the population density. To resolve this conflict, the census block data had to be merged with the census tract data. This was accomplished by using Microsoft Visual Basic, Access, and Excel.

In Microsoft Excel, both the block and tract/block group data base (.dbf) files were opened. The census block data were then copied and pasted alongside the census tract/block group data. An Excel macro was created which evaluated the census block data and determined what tract each block lied in. The macro then summed each block within a census tract and added the summed block data to the tract data. This macro effectively added all of the census blocks within a census tract. Once this macro was done running, the census block data were then deleted from the data base file with the population of each census tract remaining. Due to the fact that Microsoft Excel

2007 cannot save data as a database file, the updated tract data were saved as an Excel spreadsheet and then opened with Microsoft Access.

Using Microsoft Access, the excel file was imported, tabulated, and exported as a new database file. The new updated database file replaced the old file with the updated population data now included in the census tract database. The database file was then used by the shapefile which was read by MATLAB to process the population data to determine the population density.

MATLAB®

To calculate the population density within a PCA, the program MATLAB® created by Math Works Incorporated was used. MATLAB is a numerical computing program which has an integrated programming language that allows the user to create functions, algorithms, and user interfaces. Various functions as well as a Graphical User Interface (GUI) were written and created using MATLAB "m." files to achieve the end result of population density for a UAS flight anywhere within the continental U.S. The program was the primary tool used to calculate the population density. The specifics of the GUI and each MATLAB function used by the GUI is described in further detail in the *3rd Party Risk Assessment Tool (3PRAT) Guidebook* (Ball, 2012), reference 4.

READING IN SHAPEFILES

The first step in calculating the population density was to read the population density data for each appropriate state via the shapefiles mentioned above. In order to reduce the computational requirement needed to run the MATLAB code, only the states affected by the specific UAS mission are called out and parsed by the MATLAB functions. By doing this, the number of computations required to be performed are reduced significantly and as a result, the program can run in a matter of minutes rather than hours. MATLAB is used to determine which states fall within the UAS PCA based on the latitude and longitude of the flight plan waypoints entered in 3PRAT. Once the states affected by the PCA are determined, a MATLAB function calls in and reads the census tract for each state affected. Only the states needed are loaded and used in the computation of the population density. Each state called in is placed into a large array of data and plotted.

DEFINING THE POTENTIAL CRASH AREA

As previously stated, the PCA of a given UAS is defined per the method outlined in reference 2. The PCA of a fixed wing aircraft is a function of the aircrafts maximum glide slope, or maximum lift to drag ratio, its airspeed, and its altitude. The PCA of a fixed wing aircraft is typically elliptical in shape. However, it is important to note that as altitude increases the minor axis and the major axis of the ellipse converge making the ellipse more like a circle. The PCA of a rotor wing aircraft is a function of its forward airspeed and altitude and is circular in shape. The PCA for both a fixed and rotor wing aircraft is calculated in the 3PRAT. An example of a fixed wing elliptical PCA is shown in Figure 4 with the center position of (a,b).

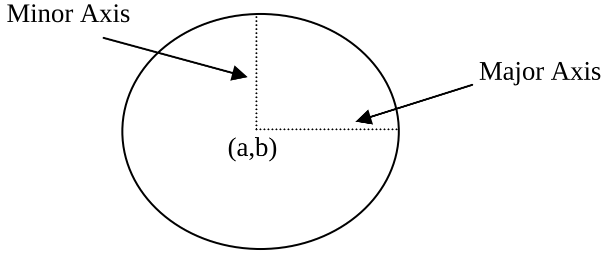

Figure 4: Elliptical PCA Example

For each waypoint entered into the flight plan tab of the 3PRAT, the vehicles altitude and airspeed is entered as well. This allows for the vehicles PCA be calculated for each waypoint. Given that an aircraft changes either airspeed or altitude between waypoints, it is assumed that the changes are uniform between the waypoints. This creates a linear change in PCA along the flight path. It is also important to note that the PCA is defined in the aircraft reference frame. To convert the PCA over to the fixed earth reference frame, a simple rotation matrix is used.

The PCA of an aircraft for any given point in time takes the shape of an ellipse or a circle. To project the PCA along a flight path, it was initially thought that the PCA shape would be projected many times along the flight path at some predefined interval. This concept can be seen in Figure 5 with the PCA shown in red being taken at 10 steps from Richmond to Charlottesville.

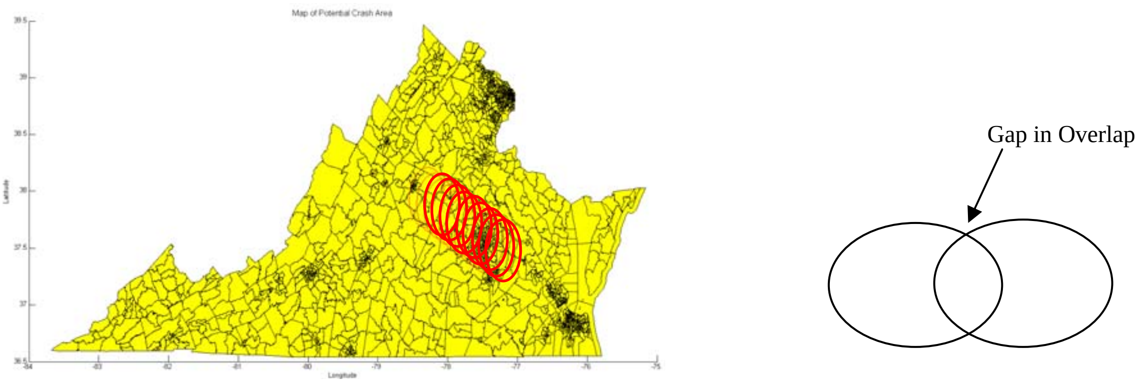

Figure 5: PCA in Virginia and Overlap Problem

Upon evaluating the method of projecting the PCA at predetermined intervals, it was determined that this would produce some amount of error in bounding the census tracts. As can be seen in Figure 5 on the right, with the overlap of the many ellipses over each other there are sections lost due to the gap in overlap. This overlap is exaggerated in the image above. Due to this potential error, it was realized that if the PCA was projected infinitely many times along the projected flight path, it would create what looked like a rectangle with a height of the ellipse diameter, capped by two half ellipses on each side. This shape can be seen in Figure 6. Not only did the rectangle method eliminate the error associated with projecting many ellipses, it also reduced the computations needed to bind the census tracts within the PCA.

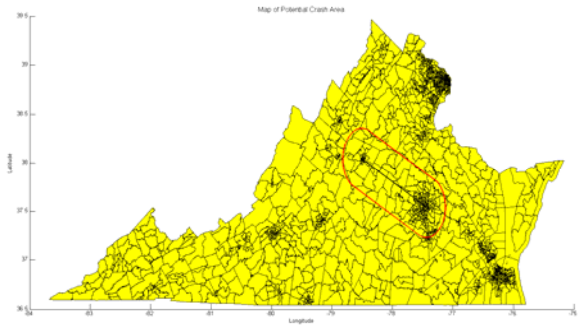

Figure 6: PCA with Infinitely Many Projections

BOUNDING CENSUS TRACTS WITHIN THE PCA

With the census tract data read and stored in MATLAB and the PCA identified, the last step required to calculate population density is to bind the census tracts within the PCA. For each census tract, data are called out from within the shapefile database. MATLAB determines if the census tract was affected by the PCA. This data included: longitude, latitude, land area of the tract, water area of the tract, and the population of each tract. Specifically, longitude and latitude is used to bind each tract within the defined PCA. Within the shapefile database, longitude and latitude data are provided for each census tract. The longitude and latitude defines the coordinates for the points around the perimeter of the census tract.

By using the geometry for each census tract as well as the geometry of the PCA, the MATLAB function “inpolygon” is used to determine if the census tract falls within the PCA. The inpolygon function evaluates points to determine if it falls within the polygon supplied to the function. By using the longitude and latitude coordinates of the census tract, an array of data were created for each census tract. This array is evaluated against the PCA to determine if the census tract lies within the PCA. If any part of the census tract falls within the PCA, the tract was bounded and counted. If the tract is counted, the population density for the tract is determined.

POPULATION DENSITY

Once the census tracts are bounded, three separate data points are collected from each tract: the area of land, area of water, and the population within the tract. The data are then used to calculate the population density within in the PCA using equation 6.

$$PopDen = \frac{PoP}{Area_L + Area_W} \qquad (6)$$

where:

PopDen = Population Density (people per square mile)
Pop = Population (people)
$Area_L$ = Area of Land Mass (square miles)
$Area_W$= Area of Water (square miles)

When comparing the population densities generated by the MATLAB code to the known population densities of various cities generated by the Census Bureau, it was noted that the densities published for the various cities where higher than what the code produced. It was realized that the calculations done by the Census Bureau only took into account the land area of the city in question when calculating population density. It is important to note that for this analysis, it is assumed that people are evenly distributed across the entire area of a census tract regardless of its land to water ratio. This was done to simplify the risk calculation as it assumed that the aircraft has an equal probability of landing anywhere within the PCA including both land and water.

RESOLUTION OF POPULATION DENSITY DATA

As previously stated, the PCA of a flight segment is defined for each waypoint in the flight plan. The 3PRAT calculates population density as the average population density for the entire flight segment. If an aircraft were to have a waypoint on the west coast of the U.S and the next waypoint on the east coast of the U.S, the tool would calculate the average population density across the entire U.S. This created a situation where it is possible to miss population density extremes within longer flight segments. As a result, it was determined that there needed to be a finer resolution in the waypoint data to capture these potential variations.

Due to the fact that there are infinitely many flight segments possible in the U.S, each segment was divided up based on its length and potential crash area geometry. In the case of higher flying fixed winged aircraft, each flight leg is divided by the radius of the potential crash area to establish how many segments each flight leg is broken up into. This method creates a finer resolution in the LoS profile for a given flight and is independent of the length of the leg. An example of the resolution increase can be seen in Figure 7. In the example, the flight on the left only included two waypoints; the start and end. However, it can be seen that by increasing the resolution, the same flight on the right is broken down to include a total of four waypoints.

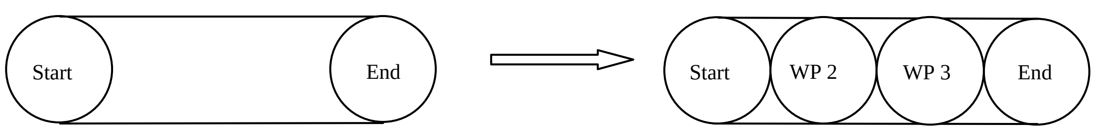

Figure 7: Resolution Increase Logic

In the case of low flying fixed winged aircraft or rotor winged aircraft, the PCA of the aircraft can become quite small and, in some cases, less than a mile in diameter. By using the above method outlined for fixed winged aircraft for rotor wing platforms, the 3PRAT became unusable due to extremely long run times as it would divide flight legs into extremely high level of a resolution. As a result for PCAs that are less than 30 miles in diameter and with flight legs longer than 120 miles, the flight legs are segmented into 30-mile increments. For PCAs that were less than 30 miles in diameter and with flights legs less than 120 miles, the legs were segmented into 10-mile increments. This method proved to effectively increase the resolution of the flights while not increasing the resolution so much that it bogged down the tool. The 3PRAT is designed to

optimize the run times required. If the user requires higher resolution, the tool can be modified to do so. It should be noted that as resolution increases, so does the run time of the tool.

MAXIMUM POPULATION DENSITY

As previously discussed, the LoS of an aircraft mission is defined by equation 1 and is a function of PLOA and POCA. POCA is also defined by equation 2 and is a function of the LCA and population density. Assuming that the aircraft's PLOA and LCA remain constant in flight, the LoS varies directly with the population density of the area in which it is operating. As a result, the extremes in the population density correlate directly with the extremes of the aircraft's LoS.

When evaluating the population density extremes, the maximum population density is a very important factor as it represents the maximum risk to 3rd parties for a given flight. To assist in the decision making process, the 3PRAT quantifies and displays the location of the maximum population density in the output data. To capture the maximum population density, code was written to capture the maximum value of the population density array created along the entire flight path. Along with the maximum value, the location of the maximum value along the flight path is stored as well. The maximum population density for a given flight is indentified by a black and red X on the map. This can be seen in Figure 8.

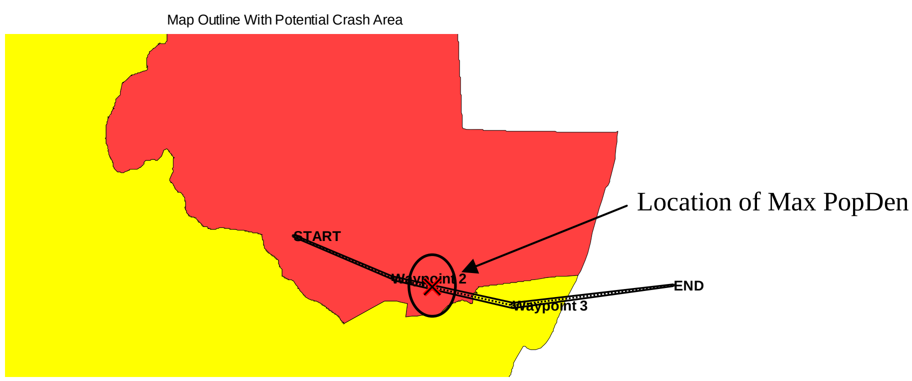

Figure 8: Location of Maximum Population Density

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2. Bradley, Natasha, Burke, David; Potential Crash Location (PCL) Model, Patuxent River, Maryland 2011.
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4. Ball, John, Andrew, Davy, Burke, David, Cochran, Roland; *3rd Party Risk Assessment Tool (3PRAT) Guidebook*, Patuxent River, Maryland, 2012.

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PATUXENT RIVER, MARYLAND

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TO:
Commander, Naval Air Systems Command Headquarters, 47123 Buse Road, Patuxent River, Maryland 20670-1547

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REPORT TITLE:
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